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GUIDELINES FOR EVALUATING THE THERMAL ENVIRONMENT OF ENCLOSED SPACES

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14. ABSTRACT
Thermal stress due to heat or cold may impact comfort, the ability to conduct operations, and, potentially, the survival of Warfighters. This report provides background information and methods for characterizing the properties of enclosed spaces (vehicles, shelters, other enclosures) that impact the thermal state of Warfighters. Quantification of the thermal environment of an enclosure consists of measuring air and surface temperatures; humidity; air flow; and radiant load. Methods focus on obtaining enough data to define each microclimate within the target space. Three studies of concrete tanks and metal containers, the High Mobility Multipurpose Wheeled Vehicle; and the Bradley Fighting Vehicle, are described.

15. SUBJECT TERMS
heat, cold, air flow, thermal stress, HMMWV, BFV, vehicles, shelters, temperature, humidity, sensors, meteorology, metrology, modeling, enclosed spaces.

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EXECUTIVE SUMMARY

Thermal stress due to heat or cold exposure impacts the comfort, ability to conduct operations, and in extreme cases, the survival of Warfighters. The purpose of this report is to provide information regarding the measurement of thermal properties of enclosed spaces to support physiological studies and biophysical modeling. The report will provide theoretical background, a description of data collection methods, and examples drawn from actual case studies. The goal is to provide the reader with a comprehensive basis for characterizing the properties of an enclosed space that impact the thermal state of Warfighters occupying that environment.

For the purposes of this paper, an "enclosed" or "confined" space will designate the interior volume of a vehicle, or other types of small interior spaces such as a tent or an intact building. By measuring the internal environment of an enclosed space, the level of thermal stress within the spaces can be determined, and the level of thermal strain (i.e., the change in thermal state and, thus, the likelihood of thermal injury) can be estimated. By simultaneously measuring the external environment, those data may be used to develop models to extrapolate the state of the internal environment when it is not possible to obtain direct internal measures.

To evaluate or monitor an enclosed space for its effect on the thermal state of the body, the potential for heat gain or loss by the various heat exchange pathways must be evaluated. The thermal state of the body may be approximated by calculating the heat balance:

$$\mathbf{M \pm W_k \pm K \pm C \pm R \pm E \pm S = 0 \quad (W \cdot m^{-2})}$$

The variables are metabolism (M), external work (W_k), conduction (K), convection (C), radiation (R), evaporation (E), and net heat storage (S). M and Wk are physiological properties, whereas K, C, R, and E are determined by a combination of physiological and environmental properties. For occupied spaces, anthropogenic heat production and moisture release (i.e., breathing and sweating) may change the internal environment.

The interior environment of vehicles and building is not independent of the outside environment. Without active heating or cooling, unoccupied spaces will reach a dynamic equilibrium with the external environment. How quickly this happens is dependent upon the mass and other material properties of the boundaries of the interior spaces, as well as how completely the boundaries enclose the spaces.

Any enclosed space consists of a matrix of microenvironments. Conditions, and the associated thermal stress, may vary significantly within a matter of a few meters. Data collection strategies are focused on obtaining enough data to define each microclimate within the target enclosed environment.

The steps involved in evaluating an enclosed space consist of the following: 1) surveying both the space and the external collection site to develop a monitoring plan; 2) measuring the dimensions of the interior space; 3) assembling sensors and dataloggers; 4) collecting data; and 5) analyzing data.

Quantification of the thermal environment of an enclosure consists of measuring T_a at selected heights and zones; temperatures of boundary surfaces (roof, floor, walls); humidity; and air flow from windows or other penetrations in the boundary, ventilation ducts, or air-conditioning units. Local heat sources (e.g., engines, stoves) or heat sinks (e.g., cold floors, walls), and solar radiation transmitted through openings also need to be quantified.

This report describes the equipment and methods used during U.S. Army Research Institute of Environmental Medicine (USARIEM) studies. Examples are presented from three case studies: one that involved monitoring large concrete septic tanks and metal shipping containers being used for a chemical-biological training exercise; one involving a High Mobility Multipurpose Wheeled Vehicle (HMMWV); and one involving a Bradley Fighting Vehicle (BFV).

INTRODUCTION

Thermal stress due to heat or cold exposure impacts the comfort, ability to conduct operations, and in extreme cases, the survival of Warfighters. The purpose of this report is to provide detailed information regarding the measurement of thermal properties of enclosed spaces to support physiological studies and biophysical modeling.

The report includes an overview of the principles of heat exchange in an effort to identify the physical parameters that define the thermal environment. It is actually more important to understand how environmental parameters impact the thermal state of an individual than to focus on specific guidance regarding instruments and methods for collecting data. The individual circumstances of a study (e.g., site access, time, availability of staff and instruments) will vary, and methodology and instrumentation will evolve over time.

The report provides a general description of data collection methods and examples of actual studies. The ultimate goal is to provide the reader with a comprehensive basis for characterizing the properties of an enclosed space that impact the thermal state of an individual or group of Warfighters occupying that environment.

Data from the cited case studies have been provided to other organizations to develop and refine thermal modeling of vehicles and vehicle occupants. They have also been used in-house to support the USARIEM efforts in biophysical modeling, the on-going development of the Physiological Status Monitoring (PSM) capabilities, and other program efforts related to environmental metrology.

GENERAL BACKGROUND

The traditional scenario of military operations being conducted by dismounted units in remote, rural locations has been augmented by more urban missions where Warfighters are both dismounted and vehicle mounted. In these scenarios, Army personnel often perform their missions in enclosed spaces that lack the climate controls (heating and air conditioning) associated with modern buildings and civilian vehicles. With inadequate or nonexistent climatic controls, Warfighters may be vulnerable to thermal stress and resultant strain. This is true even when they are partially isolated from the external environment by vehicles or structures. Conditions in interior spaces may be influenced by the exterior environment through openings, thin or poorly insulated walls, or the anthropogenic effects of the space's occupants (i.e., warm, breathing, sweating bodies producing both heat and moisture).

For the purposes of this report, an "enclosed space" will designate the interior volume of a vehicle; other types of interior spaces such as tents, bunkers, and shipping containers; or buildings without effective climate control due to lack of utility services, damage, and/or abandonment. To qualify as an enclosed space, vehicles should not be open topped, and structures should be sufficiently intact so as to substantially isolate

any occupants from the direct impact of the external environment. Building ruins or other man-made spaces that are fully exposed to the outside environment should be treated as outdoor environments with a complex topography similar to natural features like rock formations, and are thus beyond the scope of this report. In regard to fully intact buildings with operating climate controls, a large body of literature (1, 2) exists and they likewise will not be discussed in this report.

Without effective climate control, interior spaces may display daily cycles of heat and cold similar to the diurnal cycle of the outdoor environment, eventually reaching a state of dynamic equilibrium with the external environment. The amplitude and phase of these daily interior cycles, with respect to the exterior ones, are directly proportional to the availability of pathways for heat exchange and the rate of heat exchange via each pathway. The thermal mass of a building or large vehicle and/or any insulation present in the boundary structures of the interior space will slow the rate of flow of heat energy across that boundary, effectively resulting in a degree of thermal inertia. This inertial effect may both dampen the thermal extremes of the interior spaces and lead to the changes in the interior lagging behind those of the exterior. Those interior spaces with only very limited heat exchange with the external environment may not exhibit these daily cycles at all. This is especially true of spaces that are very small with respect to the number of occupants.

Enclosed spaces may be treated as a matrix of microenvironments. Thermal conditions, and the associated level of thermal stress, may vary significantly within a matter of a few meters. For example, the driver, passengers and turret occupants of a Bradley Fighting Vehicle (BFV) all experience different microenvironments. Technically, the environment is everything external to an individual. Of concern in this report are the physical attributes of the environment that have the potential to influence the thermal state of the Warfighter. Collectively those physical factors describe the thermal environment of the target individual or group.

HEAT BALANCE

To understand the impact of heat or cold exposure on Warfighters, some knowledge of thermal physiology is helpful. This section reviews basic information regarding one aspect of thermal physiology, the heat balance equation, as it relates to the total thermal state of the body. For more comprehensive information regarding thermal physiology, see Parsons (3).

The total thermal state of the body is represented by the variable for body temperature, T_b. In the laboratory it is estimated by calculating weighted averages of measured core temperature, T_c, and measured mean skin temperature, T_{sk} (4). The net effect of the environment on T_b is determined by the heat balance of the body.

$$M \pm W_k \pm K \pm C \pm R \pm E \pm S = 0 \quad (W \cdot m^{-2})$$ (Equation 1)[1]

Metabolism (M) represents internal body heat production. By convention, work (W_k) represents energy associated with lifting objects or movement on slopes. Conduction (K), convection (C), radiation (R), and evaporative potential (E) are pathways for heat transfer. The practical significance of the heat balance equation is that changes in the net heat stored (S) by the body can be directly linked to changes in T_b and, thus, thermal strain.

$$\pm S = M \pm W_k \pm K \pm C \pm R \pm E \quad (W \cdot m^{-2})$$ (Equation 2)

$$\Delta S' = (\pm S \cdot A_D \cdot t) \div 1000 \quad (kJ)$$ (Equation 3)

$$\Delta S' = c_b \cdot m \cdot \Delta T_b \quad [kJ]$$ (Equation 4)

$$\Delta T_b = \Delta S' \div (c_b \cdot m) \quad [°C]$$ (Equation 5)

The specific heat of body tissue (c_b) is 3.5 $kJ \cdot (kg \cdot °C)^{-1}$, time (t) in seconds, and body mass (m) in kg. Body mass (m) and height may be used to estimate the Dubois (A_D) body surface area (5). The value of expressing the energy balance in terms of S is that any change in net storage (ΔS') for a given time interval (Equations 3, 4) will result in a change in body temperature (ΔT_b).

A change in measurable body temperature (Equation 4) indicates a shift in the energy balance of the body. Hence, monitoring body temperature (T_b) will provide a direct indication of thermal state of the body. It is often more practical to predict the core temperature (T_c), and thermal status of the body, from a combination of weather, intensity of activity, and anthropometrics (body mass, height, posture), physiological state (hydration, fitness) and clothing properties. Equations 1-5 represent the basis for predictive modeling of the thermal effects of the environment on the thermal state of humans and other organisms. The heat balance equation thus provides a means to predict the impact of the thermal environment on the Warfighter.

The clothing worn by the Warfighter moderates heat exchange between his body's surface and his immediate environment. The values for conduction (K), convection (C), radiation (R), and evaporation (E) are modified by adjusting the heat transfer coefficients in the supporting equations to account for the resistance to heat exchange provided by clothing (6). Within very confined spaces, the bulk of the clothing ensemble, including protective body armor, may limit both the volume of the interior space and personal movement.

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[1]Preferred units for energy balance equation are as an energy flux ($W \cdot m^{-2}$) or a whole body energy exchange rate (W). A whole body energy rate is often specified for a WWII era "standard man" of 70 kg with a surface area of 1.8 m^2.

DEFINING THE THERMAL ENVIRONMENT

The rationale for monitoring the thermal environment of enclosed spaces is to determine the level of exposure of occupants to thermal stress, and of secondary importance, to determine the relative comfort or discomfort of the occupants. By obtaining environmental measurements, the level of thermal stress within the spaces can be determined, and the level of thermal strain (i.e., the change in thermal state and, thus, the likelihood of thermal injury) can be estimated. If some outside surface conditions and other external environmental parameters are also measured, those combined data may be used to develop models for estimating conditions within the enclosed space based on the external environment, the heat transfer characteristics of the structure, and other physical factors, such as any forced or natural ventilation and engine operation. It should be noted that the same biophysical principals apply to both hot and cold environments. The body of this report focuses on heat and heat stress; the Appendix discusses issues specific to cold environments.

The parameters that define the thermal environment of a Warfighter in an enclosed space are basically the same as those encountered in the outdoor or natural environment. To appropriately monitor an enclosed or confined space, the potential for gain or loss by the various heat exchange pathways must be evaluated. In general, convection (C) is a function of local differences in air temperature ($T_{\mathbf{a}}$); conduction (K) is primarily a function of the temperatures of the materials that make up the local environment; radiation (R) is determined by a combination of surface temperatures and energy transmitted through openings and translucent materials; and the evaporative potential (E) is dependent on humidity, the amount of moisture present in the atmosphere. Metabolic heat produced by the basic metabolic processes (M) and work (W_k) performed, as well as sweat produced by any occupants of the spaces being studied, are physiological parameters that will perturb the interior environment. They may be measured, or estimated using mathematical models or data from earlier research. Measurement of physiological parameters is beyond the scope of this report, but they must be considered when people, including investigators, are present in the spaces being studied.

Quantification of the thermal environment of an enclosure consists of measuring T_a at selected heights and zones, temperatures of surrounding surfaces (e.g., ceiling, floor, seats, and walls), humidity, air flow from windows, ventilation or air-conditioning units, and local heat sources (e.g., engines, stoves) or heat sinks (e.g., cool or cold concrete floors, walls). Solar radiation transmitted through windows or windshields also needs to be quantified.

<u>Temperatures</u>

Direct measurements of temperatures, specifically air and surface temperatures, will help predict heat exchange by conduction and convection. Air temperature also defines the threshold for maximum evaporative potential, and surface temperature may be used to calculate IR heat exchange. As “temperature” appears to be a factor in most

of the thermal exchange pathways, and temperature differences are easily sensed by the body, there is an intuitive tendency to try to describe the entire thermal impact of the environment in terms of temperature. However, attempting to quantify the full potential for thermal exchange (i.e., the thermal environment) solely in terms of temperature measurements tends to obscure the impact of other physical factors on heat exchange between Warfighters and their environment.

Air Temperature. There is a common assumption that air temperature is uniform throughout an enclosed space. In a few enclosed spaces, such as a small space with climate control, or a room with a large, uniform heat source or sink such as a concrete floor or ceiling, a single air temperature may suffice to describe the thermal environment, but there is rarely actually a single uniform air temperature in any given interior area. There is commonly a vertical temperature gradient from floor to ceiling. There will also likely be differences between local zones related to the temperatures of proximate surfaces and drafts or ventilation (e.g., proximity to heat vents, radiators, windows, cracks, holes). These local zones will, in many cases, define the microenvironments that make up the space under study and their identification is a critical part of the initial evaluation of the space. In a modern, climate-controlled office, these differences or gradients fall within a relatively small, predictable range. Without adequate climate controls, often the case for military personnel, the spatial and temporal variability may be greater. In most spaces of military interest, in order to adequately quantify the air temperature, multiple measurement sites will need to be utilized. It will be very important to describe them in the context of specific heights within the space, and their relationship to spatial features or physical properties. In addition, using air temperature in an attempt to fully describe the thermal environment tends to obscure the separate effects of surface temperatures, which influence the thermal state of an individual through heat transfer pathways that are independent of air temperature.

Surface Temperatures. Surface temperatures are challenging to measure accurately, as they occur at the interface between materials, typically a solid and a fluid, air or water. Temperature sensors placed at that interface may be influenced by conditions on both sides of the interface. The nature of the fluid boundary layer will affect the rate of heat transfer from the surface and from the sensor itself. Another problem with surface sensors is incident radiation, which may heat the sensor differently than the surface of interest.

This raises the question of whether or not to isolate the surface temperature sensors from external environmental influences such as solar radiation. There are several possible approaches, including reflective shielding and/or a small patch of insulated tape (such as Dr. Scholl's® Moleskin, Schering-Plough Health Care Products, Inc, Kenilworth, NJ). For very small temperature sensors with limited mass or surface area, such as thermocouples, the benefits of a solar shield are small. On the exterior surface of a large armored vehicle, the insulated tape will block sunlight and convective heat exchanges. The assumption is made that the local change in surface temperature

caused by a small patch of insulation on an object of large mass is less significant than the change in the sensor's reading caused by convective and radiative factors.

An infrared (IR) thermometer may be used as an alternative to sensors in direct contact with the target surface. An IR thermometer senses the radiant heat emitted from the surface of an object. The amount of energy emitted is proportional to the surface temperature of the object (see Equation 6, next section). IR thermometers are relatively expensive and, thus, not practical if multiple surface temperatures need to be measured. In addition, IR thermometers are not suitable for all surfaces. The IR thermometer is probably best suited for relatively flat, bare surfaces, such as blacktop, dirt, walls or vehicle surfaces, but a combination of vegetation and air space may present a problem. In recent testing, the IR-based temperatures over a grassy area were much higher than we expected based on soil temperatures. The apparent problem was that the IR thermometer was measuring the temperature of the nearest solid objects, which were the tips of the vegetation.

Radiant Heat

Radiant energy, whether from solar energy transmitted through a window and trapped within a room (greenhouse effect), or from an internal heat source such as an engine, will contribute to the total thermal stress within a confined space. Solar radiation spans a spectral range from ultra violet (UV) to the near-Infra-Red (IR) (200 to $8 \cdot 10^4$ nm). Radiation that reaches the surface of an object is reflected, absorbed or transmitted. Color affects the absorption of radiation in the visible spectrum, whereas surface roughness impacts all radiation. Smooth surfaces reflect radiation and rough surfaces absorb it. A white surface reflects more solar radiation than a black surface, but if the surface texture is the same degree of roughness, the contribution of absorbed IR to the total radiant load should be roughly equivalent.

Clear glass allows the transmission of energy in the visible spectrum, but absorbs most of the UV energy, and depending on the thickness and opacity of the medium, some visible and IR energy is absorbed. The energy content of radiation that is transmitted is not altered, but the direction of the waves may be altered (bent or diffused). Absorbed energy heats the absorbing material, and some of that energy may, in turn, be re-radiated at a longer wavelength. The surface of an object may be heated by radiation more quickly than the mass of the material. This effect is enhanced when the outer surface is made of a different material, partially insulated, or separated from the next layer.

The walls and any objects within a space, including human bodies, also emit thermal radiation. A heater or an engine radiates heat in the form of IR radiation proportional to the surface temperature of that object. The energy emitted by a wall or a human is also dependent on the surface temperature of that object. The Stefan-Boltzmann equation quantifies the energy emitted as emission of long-wave radiation (R_b):

$$R_b = \sigma \bullet T_K^4 \, [W \bullet m^{-2}] \quad \text{(Equation 6)}$$

The Stefan-Boltzmann constant (σ) is $5.67 \bullet 10^{-8}$ $W \bullet m^{-2} \bullet K^{-4}$, and T_K is the surface temperature in degrees Kelvin (T_s + 273.15).

The basic enclosed space can be modified by the presence of a radiant source or sink. When that source or sink is a point or small area source, the impact of the radiation is uneven (asymmetrical). Consequently, the orientation or exposure of the individual is an important factor in determining the impact of the radiant source.

In most cases, radiation is thought of as a source of heat (IR) gain, but a glass window can be either a source or a sink. In colder regions, the importance of windows as a heat sink is more apparent, although central heating and concerns over window drafts tend to obscure the importance of radiant heat loss.

Air Velocity (Convection)

Convective heat loss (C) is dependent on the difference between surface temperature and the fluid (air) temperature. One factor in convective heat loss is the movement of air of different temperatures in proximity to the body surface. There is an interaction between the body surface and the air. Under most circumstances, there is a layer of relatively still air close to the body (or clothing) surface or the surface of the enclosure boundary structures. The layers of stable air, the boundary layer, reduce the rate of heat exchange with the environment and, in effect, act as insulation. When the air flow is turbulent, the layers are broken up so that there is a steeper gradient between surface and local air temperature. Turbulence may be caused by obstructions or barriers that break up laminar flow or by drag as air flows over rough surfaces.

Most biophysical equations for exterior environments assume that convective heat transfer (h_c) is proportional to the air velocity raised to the 0.6 power, or approximately the square root of the wind speed. However, at low wind speeds, free convection rather than forced convection dominates heat exchange between the body surface and air, and the application of that relationship is not as reliable.

Air movement in enclosed spaces may be complex. The combination of planned ventilation, including windows, vents with fans, and other openings, like cracks or rips in walls, are quite unlike wind in an outdoor environment. Once air flow is introduced into a space, various barriers channel or block flow. In addition the temperature of walls and other surfaces can induce some patterns of air movement related to the local heating or cooling of air in proximity to those surfaces. Experimentally, smoke or other vapor could be introduced to trace patterns of air flow or leaks. This information may be used to help define the microclimates and guide the placement of air flow sensors that will enable quantification of convective heat exchange.

Humidity

Evaporative heat loss potential (E) is primarily dependent on the humidity gradient between the body surface and the surrounding air. Interior humidity will depend on the initial conditions when the access to the space is open, the amount of air exchange with the outside environment, and anthropogenic effects of occupants sweating and breathing. Pools of water, wet clothing or materials may also contribute to interior humidity. Increasing ventilation from the outside will increase the importance of the external environment relative to interior humidity and air temperature.

Humidity is expressed as a variety of measures, including relative humidity (RH), dew-point temperature (T_{dp}) and wet-bulb (T_{awb}) temperature, absolute humidity, and water vapor pressure. Although T_{dp} and water vapor pressure are probably better variables for describing the evaporative potential of the environment, RH is more readily understood by the general population.

METHODS FOR MONITORING ENCLOSED SPACES

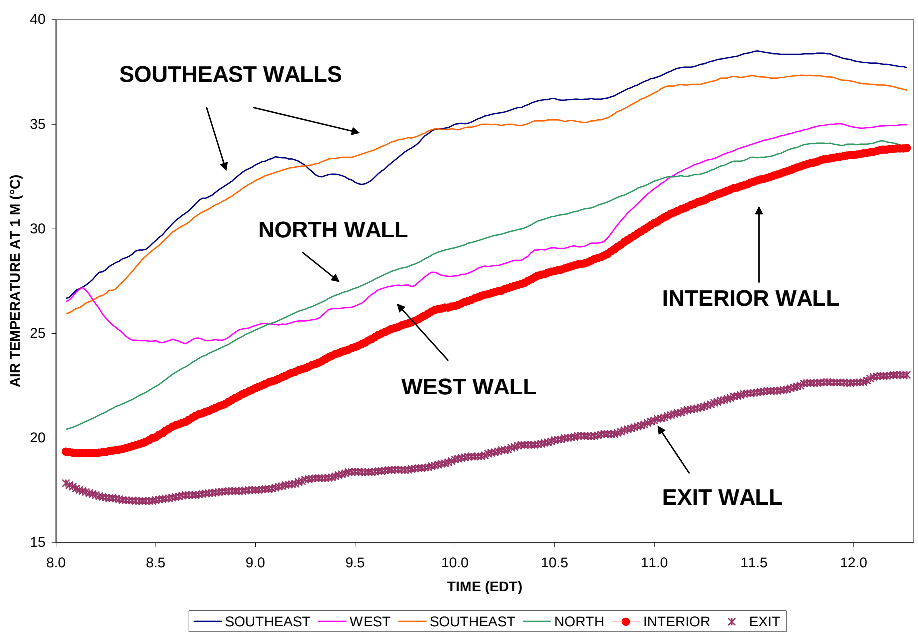
The steps involved in evaluating an enclosed space consist of 1) evaluating/ surveying the interior and collection site to identify potential microenvironments; 2) determining a monitoring plan, including both the interior spaces and external environment; 3) measuring the dimensions of the interior space(s); 4) assembling sensors and dataloggers; and 5) collecting and analyzing data.

The data collection plan should be structured to collect enough data to define each critical microenvironment within the target enclosed space (e.g., vehicle, tunnel). For example, the Bradley Fighting Vehicle (BFV) has three obvious primary zones of interest defined by interior partitions and functional uses: – the driver's compartment, the command/weapons turret, and the passenger compartment. However, in other spaces, recognizing potential interior microenvironments may not be as straight forward. In some situations, interior microenvironments may depend as much on factors external to the space as on internal ones.

For example, the East Brookfield, MA, Fire Training Site uses metal cargo containers to simulate burning buildings. They are joined together with an entry at ground level on the north end facing east and a stairway or basement bulkhead type exit on the south end, leading up and to the west. The west side of the structure was against a dirt bank (Figure 1). The walls facing to the south and east receive direct solar radiation in the morning and early afternoon, heating them up. The exterior walls facing north and west against a dirt bank, and interior walls, were cooler. A plot of the resulting interior temperatures is shown in Figure 2. The differential temperatures will drive convection currents and also provide for different radiative loads depending upon where the occupants are within the structure. See the more detailed description of the case study later in this report and the report by Buller et al., 2007 (7) for more information about the site.

Figure 1. East Brookfield, MA, Fire Training Site.

Figure 2. Air temperatures inside containers on 8 June 2007.

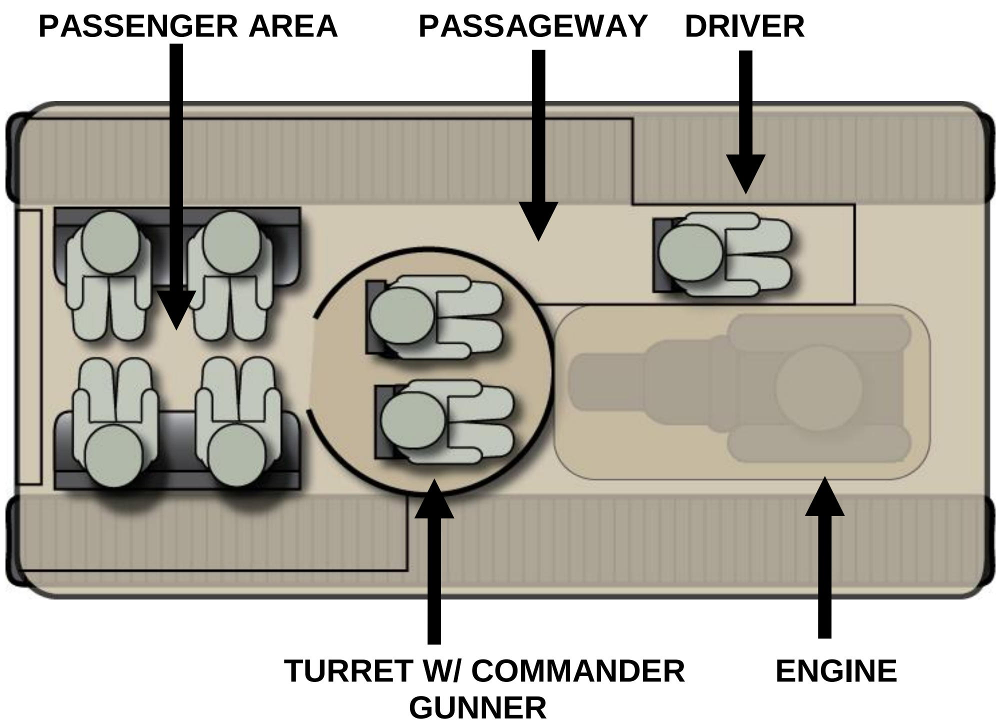


Adequate outside meteorological and exterior surface temperature data need to be collected to quantify the outside environment in enough detail to provide a database for determining the relationship between the external and internal environments. In

principle, the parameters that define the thermal environment experienced by each occupant of a unique space should be measured. The basic principle is easy to understand if we consider the function of the crew and passengers of the BFV (driver, turret occupants [commander and gunner] and infantry passenger), as each task or role is associated with a dissimilar environment. The value of instrumenting each individual's specific space becomes debatable when we consider whether we need separate measurements for the two turret occupants and each individual passenger. The BFV may carry up to six infantrymen as passengers.

The interior area of a BFV is asymmetric. Facing forward, the driver sits in the left front of the vehicle adjacent to the engine. A passageway runs along the left side of the interior to the passenger area, with an entry up into the centerline turret (Figure 3). The ventilation ports for the passengers are located on the right side of the passageway near the floor. The exposure of the passenger on the left front of the bench differs to a degree from the Warfighter seated opposite him; the bench occupants in the middle area on both benches probably experience similar environments unless one wall is warmer, but are the most influenced by heat generated by adjacent passengers. The right and left passengers on the bench next to the rear ramp are also more likely to share a similar exposure relative to mid-bench or right-left front environments. Although there are differences between each seating position, the effort required to collect data for each position probably exceeds the value of the more detailed data.

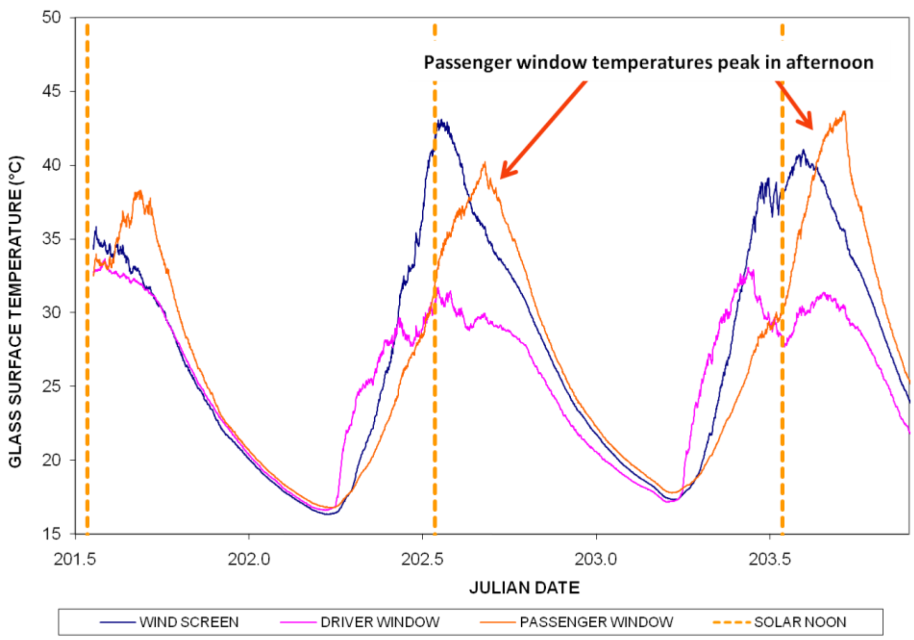
Figure 3. Diagram of the Bradley Fighting Vehicle (BFV) (Not to scale).



In most civilian housing, vehicles, and work spaces, the ratio of open (air) space to total volume is much higher than in military environments. Passenger seating in a military vehicle may be much more confined than coach seating on a commercial airliner. Vehicle engine spaces may be much less isolated from passenger spaces than in non-military vehicles. As stated earlier, within some very confined interior spaces, the bulk of the military clothing ensembles and equipment limits both free interior volume (air space) and personal movement. Anthropogenic heating and humidity are more of a concern if the ratio of air space to total space volume is small. Likewise, engine operation may have a more dramatic impact on the interior thermal environment and the occupants in very confined spaces.

When evaluating vehicles with windows, orientation relative to incoming solar radiation is an important consideration. As indicated by the HMMWV temperature plots shown in Figure 4, orientation relative to the sun is important. The effect of orientation is most clearly seen on the last day (22 July), when solar radiation was attenuated by cloud cover at the time of solar noon. The driver (east) window temperature peaks before solar noon, the Passenger (west) window peaks in the afternoon, and windscreen (south) lags slightly behind solar noon.

Figure 4. HMMWV glass surface temperatures and solar noon, 20-22 July 2007, are shown. The effect of orientation is most clearly seen on the last day, when the driver (east) window temperature peaks before noon, and the passenger (west) window peaks in the afternoon.



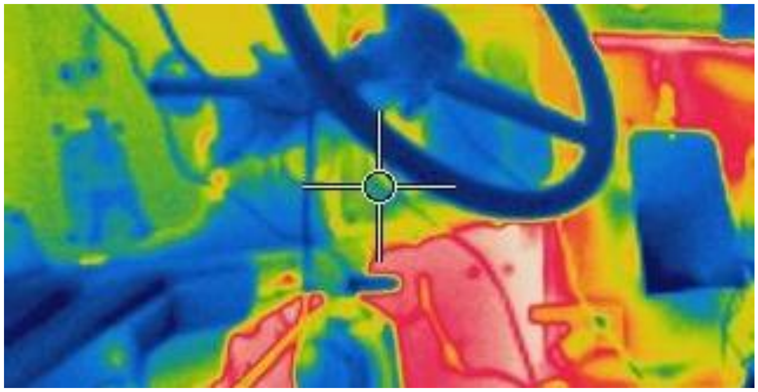
Given sufficient resources, multiple vehicles should be parked in proximity, with some oriented north-south and others east-west to capture the effects of differing solar exposures. Side-by-side placement with engine on and engine off will allow comparison despite the dynamic nature of real weather. The reality was that we usually had access to only one site or vehicle for a limited amount of time (Figure 5).

Figure 5. The HMMWV located next to the base weather station. The vehicle is facing south, and both the vehicle and station are sited on blacktop.

A visual inspection or walk-through will establish the context of the structure and the data collection site. Worst case or edge conditions relative to external factors may be determined and, for example, a vehicle may be moved so that it is maximally exposed and oriented relative to wind and sunlight. In regard to identifying unexpected heat sources or sinks, two approaches may help to identify features in advance. One is to question vehicle crews, other experienced operators, and design/material developers. The other is to use an IR imager, such as the Advanced Forward Looking Infrared (FLIR) ThermaCAM® Model E25 (FLIR Systems, Inc., Boston, MA,), to identify areas of interest for placement of sensors. The advantage of using the FLIR is that it enables investigators to pin-point the location, size, and uniformity of the heat source for placement of surface temperature sensors (Figures 6-7).

Figure 6. Infrared (IR) and color images of HMMWV interior showing temperature variations.

Forward Looking Infrared (FLIR) image

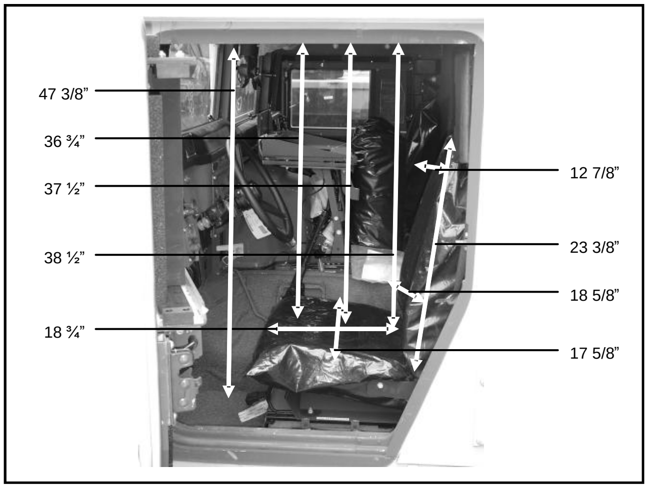


Corresponding color image

DESCRIPTION OF THE PHYSICAL SPACE

The logical place to begin developing a description of any enclosed space is a building's plans or manufacturer's schematics and specifications. However, these may be unavailable or out of date. Even when plans or blueprints are available, the team should take measurements: first, without a human figure to get the basic space dimensions; then, in context of where the occupants are in the total space. This information should help quantify factors such as head clearance, distance from instruments or dash to chest, and exposure to incoming radiant energy. Measurements should be documented with a written record and supplemented with digital images with scale (Figure 7, HMMWV driver's seat area).

Figure 7. Annotating digital images with overlaid measurements is recommended.



HOW MUCH TO SAMPLE

In terms of data handling, instrument requirements, and simplicity, the theoretical optimal situation is to collect only the requisite data. However, to collect only the minimum required data assumes prior knowledge of all critical thermal sources or sinks, all the relevant thermal questions, and proper functioning of all instruments.

The interior environments of military interest, tents, metal shipping containers, bunkers, tanks, and other vehicles are directly influenced by the external environment. In the absence of internal heat production (no engine operations or personnel), the interior temperatures should respond to the outdoor environment, with a time lag associated with the mass or thermal inertia of the structure or vehicle. It should be possible to calculate interior conditions with a reasonable degree of accuracy if the outdoor environmental parameters are known. In the absence of direct monitoring, estimates of the internal thermal environment can only be obtained by such modeling.

In addition, during the more stable night-time periods, the exterior and interior temperature of many shut-down, enclosed, unoccupied spaces should approach equilibrium. This can be an important built-in instrument check against gross sensor error. There is a tendency not to collect data for extended periods of time, but 24-h data collection can isolate different meteorological effects, the most obvious being that of solar radiation.

Instrument redundancy is partially a question of data monitoring resources, access to repair or replacement resources, logistics, and time. Quality instruments that have been carefully tested with the associated data acquisition systems (dataloggers) prior to testing generally do not require back-up. However, when instruments are used at remote sites far from support, or deployed over extended time periods, or when time constraints preclude thorough on-site checks, redundancy has some merit.

Unfortunately, the more remote a deployment site is, the more likely it will be that simplicity and a low logistic footprint will also be valued assets.

No one can fully anticipate new questions, or questions that may develop from the initial analysis of the data. Collecting additional "might-be important" data has value, provided the effort required to collect the data is manageable. Few investigators have complained of having too much data.

OTHER CONSIDERATIONS

Excessive heat, cold, excess dirt, or oil may impact tape or other adhesives, damage or otherwise impact sensor performance. An alcohol-based spray cleaner was used during the BFV study to clean the vehicle exterior surfaces to allow tape to hold thermocouple sensors in place. Care should be taken when attaching or removing test materials to avoid damage to surfaces and vehicle controls.

If data collection requires occupants or operators of the spaces, and on-site investigators, some additional guidelines are in order: 1) safety first, 2) don't place sensors in locations that interfere with operators or function of equipment, 3) safety shoes, clothing, gloves, hard hats, flashlights, knee pads, water, and breaks should be planned, as required. When testing conditions exceed those encountered during normal operations or training, rules for human use testing may apply (AR 70-25) (8). If monitoring of test participants (drivers, passengers) is performed, volunteer agreements and photo releases may be required. Normally, test staff members are exempt from monitoring requirements unless they also function as test subjects. However, when testing is conducted in extreme environments, the safety of staff **must** also be considered.

INSTRUMENTATION

The basic science underlying the various meteorological sensors has been discussed elsewhere (9). Various parameters can be measured with a variety of instruments. For example, air movement can be measured as mechanical force by cup and propeller anemometers; electronically, as the power requirement to maintain a constant temperature with a hot-wire anemometer; as a pressure drop in a pitot tube; or a disruption of sound waves with a sonic anemometer. For the sake of simplicity, we will focus on the sensors we actually used rather than all of the options (Table 1).

On occasion, a non-standard sensor is useful. Determining the net radiant load on occupants of an enclosed space is difficult, as the load is a combination of direct, diffuse, and reflected solar, sky, and ground long-wave IR incoming radiation sources, minus the thermal radiation emitted by the occupants. Black globe thermometers are not a standard meteorological sensor, but the instrument integrates a complex set of meteorological variables (T_a, solar, and long-wave IR radiation, and wind speed) into one measurement – black globe temperature (T_{bg}). As the radiometers used to measure solar and IR radiation are often not effective in small, enclosed spaces, 15 cm

black globe thermometers were used in several of our studies to characterize the radiant load. A variable representing the combined radiant load on a standing man, mean radiant temperature (MRT), used in thermal models to predict T_c and other physiological responses to heat (or cold exposure), may be derived by removing the wind effect.

Table 1. List of Sensors, Recording Devices, and Instruments.

Description	Model	Comments*
Dataloggers	CSI CR10X	Base weather station w/radio link, solar and battery powered, customized weather sensor set
Dataloggers	CSI CR23X	Battery powered, customized sensor set
Dataloggers	CSI CR21	Battery powered, customized sensor set
Dataloggers	CSI CR7	Multi-channel logger with expansion cards (28+ thermocouples), battery or AC power.
Weather station	ADA WeatherPod™	Portable, self-contained weather station – air temperature, humidity, sonic anemometer with solar sensor, radio link, battery, and solar power
Temperature/ humidity recorder	Onset HOBO Pro V2	Simple put and forget, record only units – post hoc down-load
WBGT monitors	Quest QuesTemp°34	Recording monitor with dry bulb, wet bulb, black globe temperature sensors, and RH sensors – calculates WBGT index, and real-time link option
IR imaging	ThermoCAM® FLIR E25	Infrared (IR) camera
Temperature/Humidity	Vaisala HMP 45 w/shield	Combination temperature and humidity sensors placed inside ventilated solar shield (Gill)
Air temperature and surface temperature	Thermocouples thermometers	Hand-assembled 28 gauge copper-constantan thermocouple thermometers
Surface temperature	Apogee IRTS-P	IR radiometer
Ground temperature	CSI 105/107/108 thermal probes	Thermocouple and thermistor probes for air, soil, water, etc.
Solar radiation	LI-COR LI200 pyranometer	Silicon diode – not for indoor use
Solar radiation	Hukseflux LP02 pyranometer	Thermopile sensor element – may be used indoors
Black globe thermometer	Commercial (original source unknown)	Black painted, 15 cm spun copper globe with thermistor or thermocouple temperature sensor
Wind speed and direction	Wind Sentry Set (R.M. Young 3001)	Combined unit with cup anemometer and wind vane
Air velocity	Extech Model 407123 Hot Wire Thermo-Anemometer	Hot wire anemometer
Barometric pressure	Setra Model 278	

*Additional information regarding manufacturers may be found in the text.

Dataloggers

USARIEM uses three types of dataloggers or recorders: research grade meteorological dataloggers with individual sensors, miniaturized weather stations with integrated sensors, and stand-alone logging sensors. Our primary dataloggers are research grade instruments from Campbell Scientific Instruments (CSI, Logan, UT), which provide both real-time displays and store data from a variety of sensors. They are quite flexible in terms of the types of sensors that can be supported, and data collection is readily customized to fit a particular study scenario. The disadvantages of the CSI datalogger/sensor set-ups depend on the specific set-up, but may include weight, the necessity for hard-wiring of the individual sensors into a terminal strip, and set-up time relative to integrated systems with built-in sensors. When a number of sensors and/or instruments are used, management of wires and cables in a confined space is a matter of concern. Taping down wires and cables, and bundling wires are important considerations to managing a flexible or custom set-up. The CSI outdoor weather station (Figure 8) is based on the CSI 10X datalogger, and uses a 2 m tripod, solar panels, and individual sensors.

Figure 8. A base weather station. Meteorological measurements include air temperature, humidity, surface temperature, solar radiation, wind speed, and direction.

Miniaturized WeatherPod™ (ADA Technologies, Littleton, CO) weather stations that measure air temperature, humidity, air pressure, wind speed, and solar radiation (day/night and approximate intensity) were also used during USARIEM tests. The WeatherPod™ is a new lightweight (1 kg) device, developed under a Small Business Innovation Research (SBIR) project with USARIEM. Data were telemetered to a laptop computer for display and storage.

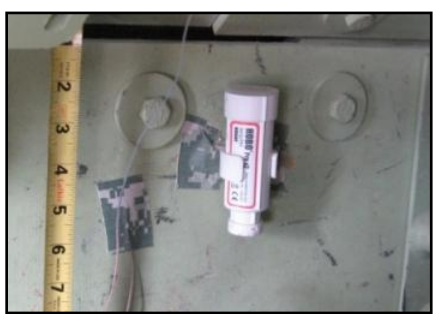
The WeatherPod and similar products provide a highly portable, easy-to-set-up package relative to the CSI base weather stations. A female camera connection allows the device to be easily set up using a tripod or other camera mount. The disadvantage of the miniaturized stations is that some data are not “research” quality data, as the

instruments are not individual top-of-the-line instruments, but sensor elements integrated into one device. Some measurements, such as air temperature and humidity, do not follow rigorous professional standards for meteorological data collection.

While accepting less than the very best possible data may be of some concern, miniaturized weather stations are practical solutions for field studies, given the realities of variability in the outside environment, portability, and cost. The lower logistic and cost factors allow more measurements of the outdoor weather for the same investment. In environments that are complex in terms of weather, such as a site with asymmetrical exposure to wind, sun, ground temperature (grass, sand, and blacktop), and bodies of surface water, an array of weather stations will provide more information than a single base station.

The HOBO® Pro v2 temperature/RH loggers (Onset Computer Corporation, Pocasset, MA) are an option if real-time data are not required. The units are easy to use and are quite suitable for placement on the walls or other surfaces of a manned vehicle (Figure 9). However, when fixed to those surfaces, measured temperatures are neither surface temperatures nor wholly representative of the air temperature of the more open areas of the enclosure. A major advantage is that as self-contained, passive sensor/loggers, there is no signal transmission to interfere with communications or other electronic equipment. The relatively low profile and lack of external wires or connection also make the HOBO or similar devices ideal to "put and forget" when testing moving vehicles or aircraft in flight. The primary disadvantage of this and other similar simple data recorders is that sensor function can only be checked by down-loading data; there is no real-time data.

Figure 9. Temperature and humidity sensor (HOBO v2, Onset Computer Corporation, Pocasset, MA).



Temperature Sensors

The only practical method for monitoring a large number of temperatures in an enclosed space is to use electronic temperature sensors rather than analog devices. Although manufactured thermistor temperature and Resistance Temperature Detectors (RTD) sensors present certain advantages, the small size, flexibility, and the ability to

construct or purchase large numbers of thermocouple sensors made them a logical choice.

The temperatures of interest in a confined space are air and surface temperatures. The meteorological standard for air temperature is to measure temperature using a shaded but well-ventilated instrument. Thermometers were traditionally placed in a small, white-painted box with a ventilated door for access. For modern electronic stations, a plastic cylinder resembling an inverted stack of small pie plates – a Gill radiation shield (e.g., R.M. Young M-41003, Traverse City, MI) – shields the thermometers from solar radiation while allowing air flow around the temperature and humidity sensors (Figure 10).

<u>Surface or Soil Temperature Sensors</u>. In addition to the adaptation of small gauge wire thermocouple sensors to measuring surface, other temperature sensors have been specifically designed for use in direct contact with damp or wet substrates. As part of exterior environment monitoring, surface and ground temperature may be measured with sensors that are protected by metal or plastic so that they can be buried or submerged at selected depths (e.g., 5 cm, 10 cm) without damage (CSI 105/107/108 temperature probes). Attention should be paid to the sensor temperature exposure range, as sensors are often optimized for a specific application. Soil and surface temperatures may be much higher than air temperatures. An upper limit for a soil temperature probe may be 20+°C higher than the most extreme anticipated air temperature. The ground temperature probes are rugged and inexpensive, but it is difficult to get a value right at the surface. IR thermometers (Infrared Thermocouple Sensor Radiometer [IRST], Apogee Instruments, Logan, UT) allow a measure of an actual surface temperature within the limitations stated in the section on surface temperatures, but are more fragile and expensive than the ground temperature probes.

Figure 10. Interior of HMMWV showing Gill shield enclosing a temperature/humidity sensor.

Custom Sensor Mounts – PVC Man. In our evaluations of enclosed spaces, the primary objective is to predict the biophysical reaction of a seated human to the interior environment. One solution to replicating the spatial attributes of a person is to place a life-sized manikin in the seat and use the manikin as a sensor mount. The problems with such manikins are cost, weight, and portability. In addition, while surface measurements may be of value, the values of actual interest may be the temperature, humidity, and radiant load within the space, rather than on the surface of the object, so the active part of the sensors may need to be held several centimeters from the surface. To address these needs, "PVC Man," a ladder-like framework of ½" polyvinylchloride pipe (PVC) and connections, was created (Figure 11). The lightweight framework "sits" on a seat, and is used to support sensors, either on short lengths of PVC pipe, wires stiffened with plastic strips from tie-tabs, or flattened, wooden craft sticks. The "PVC Man" mount is very light-weight and can be readily broken down into short lengths for transport. During field studies, once the general dimensions are determined, the materials may be purchased in any large building supply store. A device like the PVC Man mount will allow air temperatures to be collected in the context of the occupant of the space.

The sensors used with "PVC Man" were primarily thermocouples. We also used a black globe temperature sensor mounted on a short PVC stalk or neck in either the head or center of mass. Humidity sensors may also be attached to the frame or a stalk at any desired location. The zones of interest are generally the head, chest, knee or thigh, and foot areas, but the basic design is adaptable to other zones and/or more sensors.

Figure 11. Photograph of "PVC Man" mount for thermocouple thermometers and black globe thermometer in passenger seat of HMMWV.

Humidity Sensors

Although numerous types of humidity sensors exist, simple electronic sensors are compact and inexpensive. Although the sensing element is based on electronics, humidity sensors are not stable over extended time periods and require periodic calibration. Our primary humidity sensors are the HMP 35/45 series (Vaisala Oyj, Vantaa, Finland). These provide temperature and humidity outputs and are typically placed inside a Gill shield. Although we have not used it extensively, the more compact HMP 50 will allow more temperature/humidity reading in tighter spaces if used without a shield. The CSI datalogger programs include the option of reporting humidity as RH, $T_{dp,}$ or T_{awb}. For our work, the HMP sensor was supplemented by HOBO temperature/humidity sensors. The Quest WBGT monitor measures both natural wet-bulb temperature (T_{nwb}) and RH.

Exterior Solar Radiation

Radiometers that measure solar radiation are called pyranometers. A pyranometer consists of a sensor element, usually a thermopile or silicon diode, configured as a flat disc underneath a glass dome. The glass filters out some UV and IR radiation. The base for the sensor element has a bubble level and adjustments screws. The most common outdoor mount is a platform or arm that holds the instrument in a level, horizontal position so the sensor is fully exposed to the sky. In that configuration, the pyranometer measures “global radiation,” the combined direct and diffuse solar radiation from the sky. A pyranometer can also be mounted facing the ground to measure reflected solar radiation, and other configurations can separate diffuse and direct solar radiation. Direct solar radiation is the direct beam of radiation from the sun, and diffuse radiation is the sky or scattered solar radiation minus the direct radiation. On a completely overcast day, virtually all solar radiation is diffuse.

Interior Radiant Load

Pyranometers using silicon diodes are calibrated only for exposure to full spectrum of sunlight (LI-COR 200X, LI-COR Biosciences, Lincoln, NE) and, thus, are of limited value in enclosed spaces. Thermopile sensor elements (Hukseflux LP02 pyranometer, Hukseflux Thermal Sensors B.V., Delft, Netherlands) measure the radiant heating effect and are not dependent on the spectral distribution of the incoming radiation. Thus, it is possible to use pyranometers with thermopile sensors inside buildings, but the configuration of the instruments is not ideal for enclosed spaces. As the radiometers used to measure solar and IR radiation in outdoor environments are often not effective in small, enclosed spaces, black globe thermometers were used in several of our studies to characterize the radiant load. The black globe thermometer described earlier (Figure 12) consists of a hollow copper sphere, painted flat black, with a temperature sensor in the center. The standard diameter is 15 cm (6”). With a 15 cm globe, there is generally a lag time of 15 min or more as the sensors equilibrate with the environment. Many commercial sensors use smaller globes, which save space and respond more quickly to changes in temperature and air velocity. The values from the

smaller globes are adjusted to represent a 15 cm globe, but the algorithms used to make the adjustments are proprietary information.

Figure 12. A 15 cm black globe thermometer mounted in the passageway behind the driver's compartment leading to the passenger zone. The curved shape is the wall of the turret.

Wind Speed/Air Velocity

In an enclosed space with low air flow velocity, the force of the moving air is often insufficient to overcome the inertia or stall speed of the familiar cup anemometers. Space limitations and the stall speed of mechanical anemometers usually make them impractical for interior measurements. Mechanical anemometers are often available in a set with wind vanes (Wind Sentry Set, M-3001, R.M. Young, Traverse City, MI), but the direction of air movement in enclosed spaces is generally predictable enough that a wind vane is not a useful interior instrument. Sonic anemometers use the distortion of an acoustic signal to determine wind speed and direction, but are likewise generally not suitable for interior spaces. The preferred device is usually an electronic anemometer with a heated sensor element, such as a wire or small sphere. Air velocity can be derived from the power required to maintain the sensor element at a set temperature, which is proportional to the convective heat loss to the environment. The merits of an electronic anemometer (Model 407123 Hot Wire Thermo-Anemometer, Extech Instruments, Corporation, Waltham, MA) are sensitivity to low air velocities, direct measurement of convective heat loss, and the compact size of the sensor element, which is usually mounted on a small wand that can be inserted into vents. The disadvantages are the power requirements and the relatively delicate nature of many hand-held electronic anemometers.

RESULTS FROM CASE STUDIES

The following case studies demonstrate how data were collected in the field for three enclosed space studies in 2007. The Civil Support Team (CST) data were collected during joint training session with the 1st Civil Support Team- Weapons of Mass Destruction (1st CST-WMD) and Massachusetts State Police. The High Mobility Multipurpose Wheeled Vehicle (HMMWV**)** study was conducted on the grounds of

Natick Soldier Center, Natick, MA. The Bradley Fighting Vehicle (BFV) was instrumented during equipment testing at Yuma Proving Ground (YPG), Yuma, AZ.

CIVIL SUPPORT TEAM-WEAPONS OF MASS DESTRUCTION (CST-WMD) ENCLOSED SPACE

This exercise consisted of a 2-day training exercise with the 1st CST-WMD Team in conjunction with the Massachusetts State Police in the North Brookfield and East Brookfield, MA, area. For a complete description of the study, see Buller et al., 2007 (7). The training took place at two locations on 7-8 June 2007. A 2 m weather station (CSI 10X) recorded outside air temperature (1.5 m), humidity (1.5 m), wind speed (2 m) and solar radiation (1 m) at 1 min interval. Weather station data were available on a laptop display. The training at both sites consisted of team entries into confined spaces to execute a rescue. Due to the tight space, no sensors or dataloggers were placed on the floor of the interior spaces. Inside sensors were limited to wall mounts. At the first location (Chase Precast, North Brookfield, MA), the training area consisted of two stacked empty septic tanks (Figure 13) that were entered via a small opening in the top. The base of the bottom tank was elevated off the ground, and the fit between the two tanks was not tight, so there was air flow on the bottoms of the tanks, as well as through the upper openings (Figure 14). The tanks were instrumented with HOBO Pro v2 air temperature and humidity sensors that recorded data every 1 min. The HOBO sensors were placed on ceiling, floor, and walls (Figure 15); they were placed 1 m from the floor on all walls (north, south, east, west) and additional sensors were placed 0.5 m from ceiling and floor on east and west walls. Results (Figure 16) indicate that the upper tanks were slightly warmer and, based on T_{dp}, less humid (Figure 17). The mean difference between the upper and lower mean air temperatures is 0.5°C for the time interval 0900-1400 h. The mean difference in chamber T_{dp} (upper chamber mean - lower chamber mean) is -0.7°C. A lower mean indicates less humid conditions. Outdoor humidity (Figure 17) appeared to be more variable, but this may reflect the smoothing effect of using mean values for the interior measurements. We attempted to collect air velocities with a hand-held weather monitor (Kestrel 4000, Kestrel Meters, Sylvan Lake, MI), but air velocities were below the stall speed (<0.4 m/s) of the miniature propeller anemometer.

The second site, the East Brookfield Fire Training Site, consisted of metal shipping containers and is described earlier in this report (Figure 1). HOBO Pro V2 sensors were placed inside, and the same outdoor weather station used the previous day was moved to this site on 8 June 2007. As noted previously, the walls receiving direct solar radiation in the morning and early afternoon were warmer, whereas the walls not receiving direct sunlight were cooler (Figure 2). The wall at the top exit on the south end was also cooler. When humidity is plotted as relative humidity, there appears to be large differences in humidity (Figure 18). However, when plotted as T_{dp} (Figure 19), the humidity is nearly equal along all of the interior perimeter (outer) walls (South and Southeast, West, North) until about 10:45 h, and higher for the interior wall. Whether expressed as RH or T_{dp}, humidity values are higher in proximity to the interior

wall, but using RH tends to mask the uniformity of values along the interior perimeter walls.

Figure 13. The initial CST-WMD training site was a concrete casting site. The teams practiced entry and evacuation of a casualty from two stacked, open-bottomed septic tanks. A third tank was placed in front of the two stacked tanks.

Figure 14. The septic tanks were entered through an opening in the top of the tanks. To avoid interfering with the training, only wall mounted HOBO Pro v2 temperature/humidity sensors were used inside the tanks. One is taped to the wall just above and behind the worker exiting the lower tank.

Figure 15. A HOBO Pro v2 temperature/humidity sensor placed on the wall of a septic tank.

Figure 16. Mean air temperatures at 1 m in for upper tank, lower tank, and all temperatures combined, on 7 June 2007. Error bars are ±1 SD.

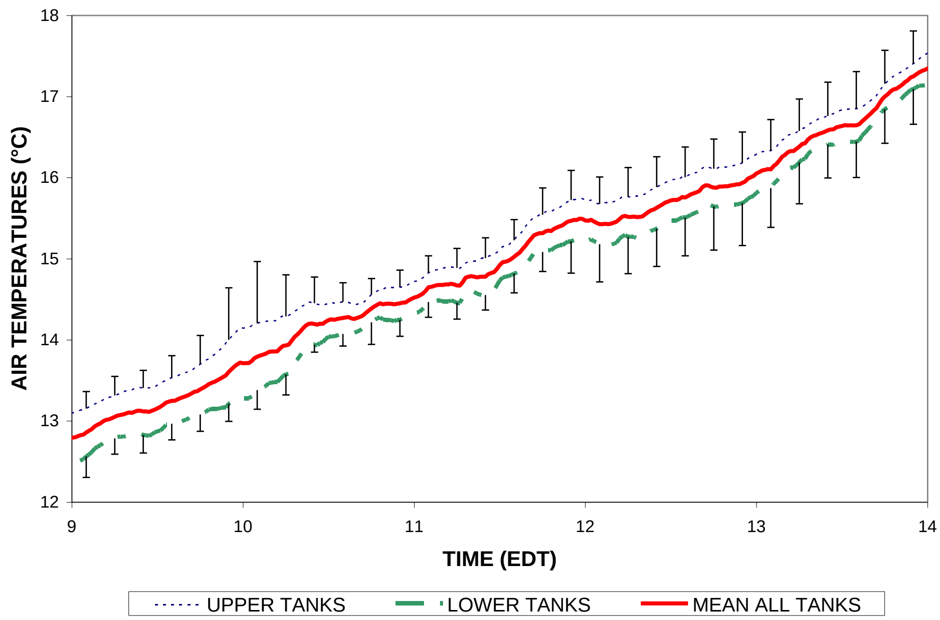


Figure 17. Comparison of mean dew-point temperature for upper and lower tanks to mean for all HOBO sensors at 1 m from tank bottom, plus outdoor dew-point temperature on 7 June 2007. The upper tanks are less humid than the lower tanks. Interior conditions are more stable than exterior conditions, and tend to be drier.

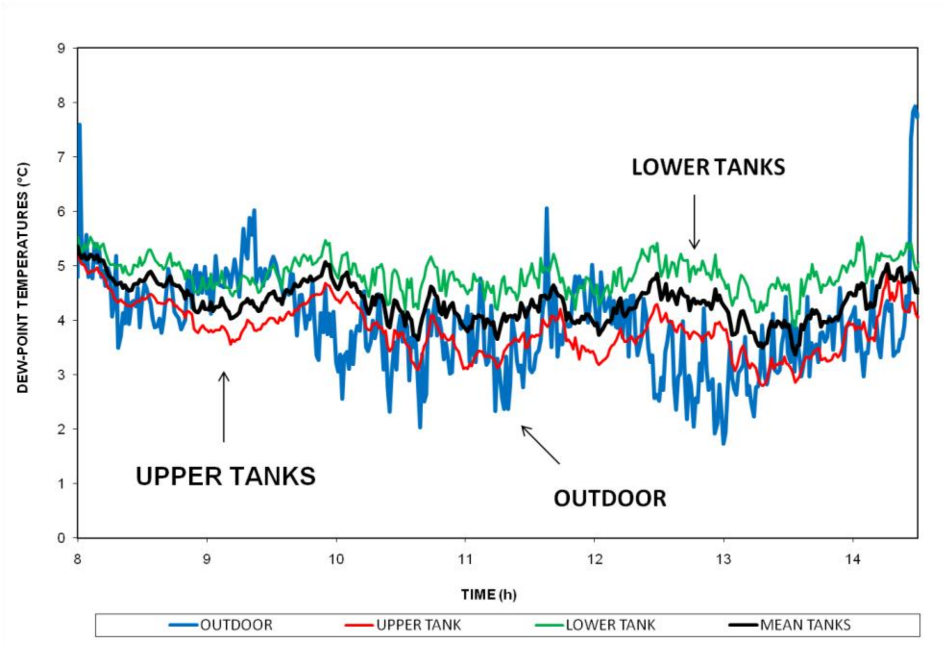


Figure 18. Relative humidity inside the containers on 8 June 2007. Note apparent large difference between locations.

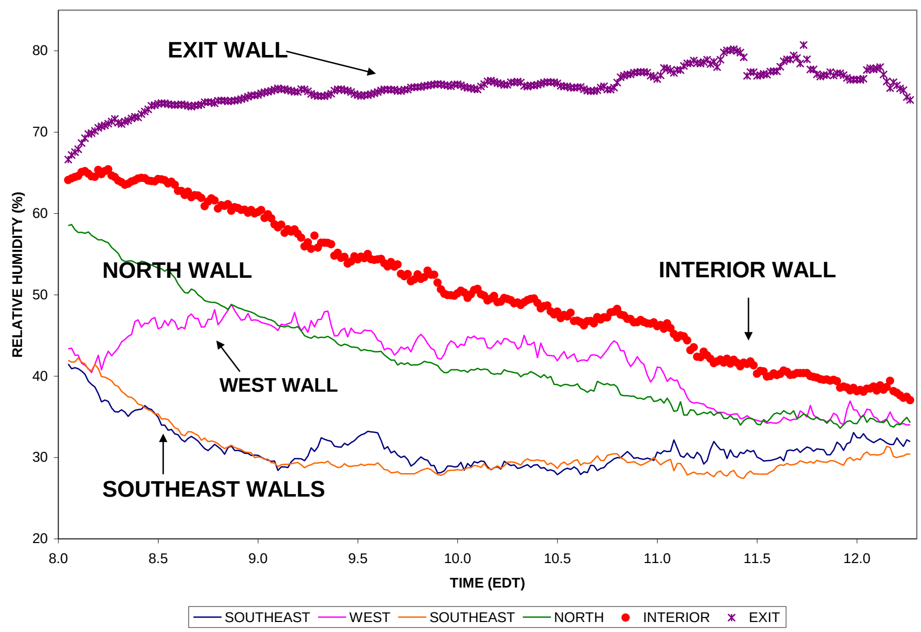
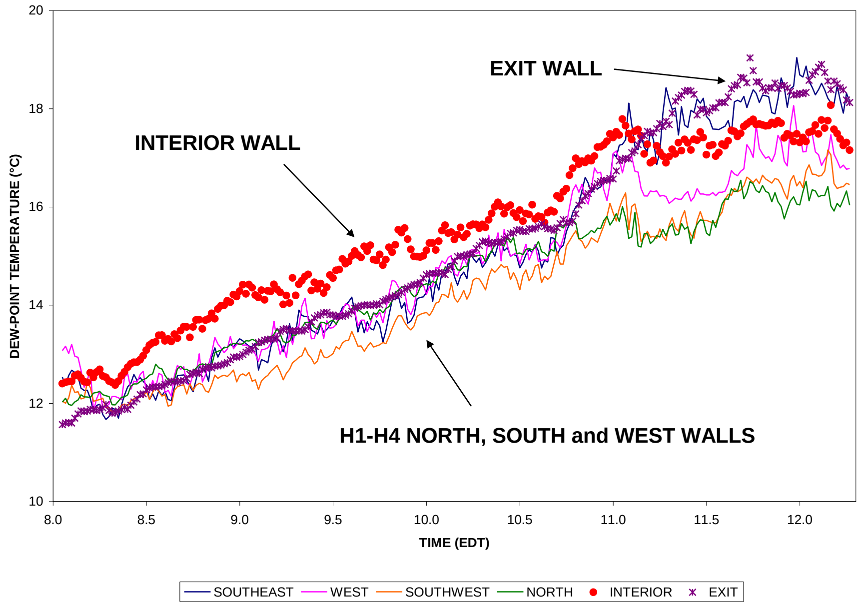


Figure 19. Dew-point temperature inside the containers on 8 June 2007. Note that perimeter wall values are uniform until approximately 1045 h. The humidity along the interior wall is higher.



HIGH MOBILITY MULTIPURPOSE WHEELED VEHICLE (HMMWV)

Test Set-up

An up-armored HMMWV was oriented with windshield facing south on the edge of a parking lot. The vehicle was tested in the buttoned-down mode with windows and doors completely closed. The engine was either shut down or turned on with or without AC. Data were logged with a Campbell Scientific Instruments (CSI) 10X, CSI CR23X, and two CR21X dataloggers. Limitations of the site included other vehicles close to test vehicle, a lake to the east, trees blocking early sun and wind from the east, and a hill blocking late sun and wind (Figure 5). Air velocities for driver, passenger, and air vents were measured with a hot wire anemometer (Model 407123 Hot Wire Thermo-Anemometer, ExTech Instruments, Corporation, Waltham, MA). Access to vehicle plan and careful measurement of interior generated an excellent table of measurements (Table 2). Figure 7, presented earlier in the report, shows how the measurements were documented with digital images.

External Meteorological Measurements

The outdoor weather station (CSI CR10X datalogger with solar panels) monitored shielded air temperature and humidity (1.5 m), wind speed and direction (2 m), global radiation (1.7 m), and an IR surface temperature. Figure 20 plots external air and dew-point temperatures, plus RH. Instruments include a shielded air temperature and relative humidity sensor (HMP 45, Vaisala Oyj, Vantaa, Finland) at 1.5 m, a

pyranometer (LI200, LI-COR Biosciences, Lincoln, NE) for global solar radiation, wind speed, and direction at 2 m, plus barometric pressure (Table 3).

Table 2. List of HMMWV Dimensions with Description and Measurements in Inches. (Sample -- table truncated).

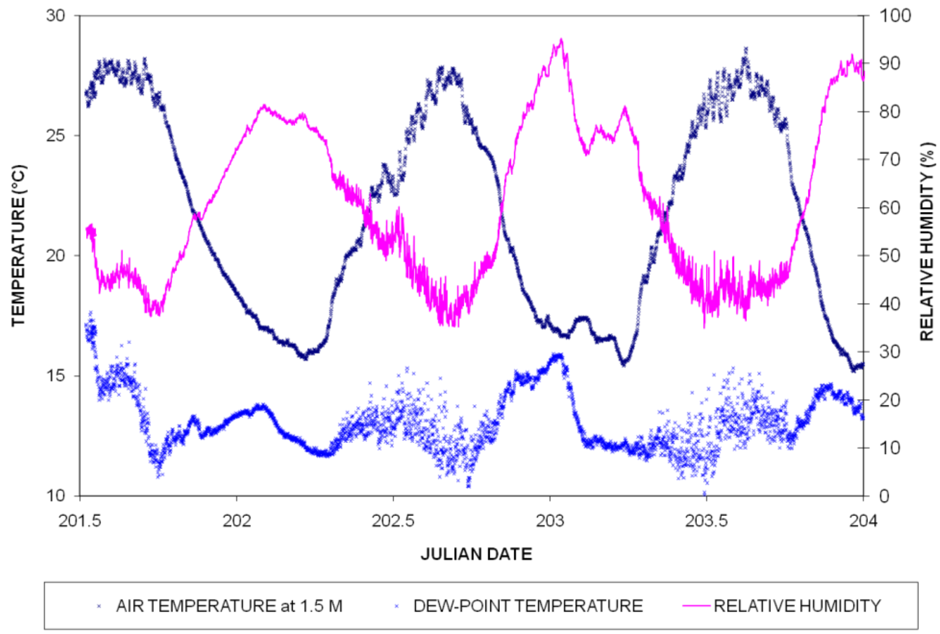
Description	Value
Back wall – length	186.7
Distance between seats (at largest distance)	109.2
Distance between seats (at smallest distance)	99.1
Insulation depth	2.5
Width of vehicle	218.4
Total length of vehicle	491.5
Length of truck bed	218.4
Height of vehicle	193.0
Height from floor to ceiling	120.3
Height from seat to ceiling (front)	93.3
Height from seat to ceiling (back)	97.8
Seat base - length	47.6
Seat base - width	44.8
Seat back - height	64.5
Seat back - width (at widest)	47.3
Seat back - width (at narrowest)	32.7
Side window - height	30.8
Side window - width	40.6
Door - height	109.9
Door - width (at widest)	82.6
Door - width (at narrowest)	66.0

Table 3. Sensors Used to Measure Parameters of the External Thermal Environment.

Weather Measurements: CR10X Datalogger

Variable	Sensor	Comments
Air temperature	HMP45C	Shielded
Relative humidity	HMP45C	Shielded
Wind direction	Wind Sentry	360°
Ground temperature	IRTS-P	IR thermometer
Global solar radiation	LI200X	Also Solar kJ
Wind speed	Wind Sentry	m/s
Barometric pressure	Setra 278	mmHg

Figure 20. Exterior air temperature, dew-point temperature and relative humidity, 20-22 July 2007, during HMMWV testing. Note the inverse relationship between air temperature and relative humidity. Relative humidity peaks near dawn, and air temperature peaks after solar noon.



Vehicle Orientation

An important aspect when testing vehicles with windows is the orientation of the vehicle relative to the sun. Direct solar radiation, the beam of solar energy transmitted directly from the sun to the target object, or what is generally termed "direct sunlight," can heat the interior of a vehicle. The dash, seats, and other objects inside the vehicle including the passengers are heated. A vehicle with closed windows is a “greenhouse,” and heat tends to be trapped inside.

Another factor is that as the sun rises higher in the sky, the roof of the vehicle may begin to shade more of the interior. However, with a steeper angle the direct radiation has a plunging effect that penetrates more deeply towards the floor so that the lower body, dash, etc. may receive more intense radiation (Figure 21). An interesting side effect is that when direct solar radiation intensity peaks with the maximum solar elevation (solar angle), the absorption of direct solar energy may plateau or even decrease, yielding a bi-modal distribution of maximum absorption. It is therefore important to know how the vehicle windows and roof are oriented relative to the sun.

Exterior Surface Measurements

Exterior surface temperatures were measured with copper-constantan thermocouples (Table 4) insulated with moleskin covered with an additional layer of reflective tape. The eight temperatures were recorded with a CR21X datalogger. Figure 22 plots the placement of the temperature sensors on the surface of the vehicle. Figure 23 shows the mean value for the metal (n=4) and glass (n=3) surface temperatures. Figure 4, shown earlier in this report, plots the surface temperature of the driver, passenger, and windscreen glass.

Figure 21. Effect of solar angle on vehicle at dawn (horizontal, i.e., solar angle = 0) and solar noon (solar angle ≈ 68° for latitude and time of year). If vehicle is facing east at dawn, direct sunlight will strike back of vehicle cab. If facing south at sunrise, the direct beam will transverse from driver to passenger side through small side windows. At solar noon with vehicle facing south, back of cab is shaded by roof, but dash is heated by direct sunlight. In tropical and subtropical areas where solar angle is greater (near 90°), almost all of the interior will be shaded at solar noon. (Figure modified from http://www.fas.org/man/dod-101/sys/land/m998.htm accessed on 24 June 2008.

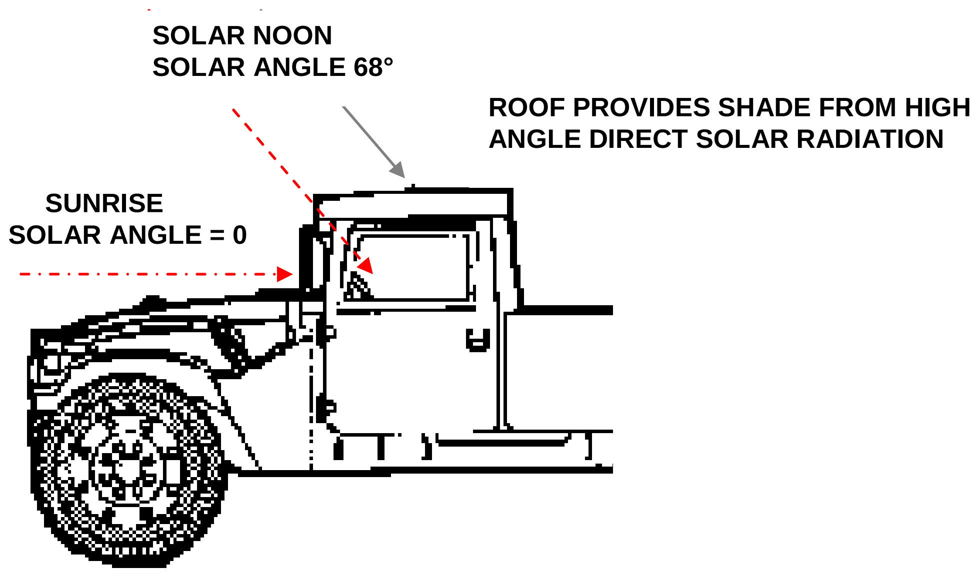


Table 4. Placement of External Surface Thermocouples.

Location
Exterior – Roof
Exterior – Windshield
Exterior – Cabin Back Panel
Exterior – Driver Door Glass
Exterior – Driver Door Panel
Exterior – Passenger Door Glass
Exterior – Passenger Door Panel
Exterior – Hood

Figure 22. Top view of HMMWV showing the location of exterior surface temperature sensors.

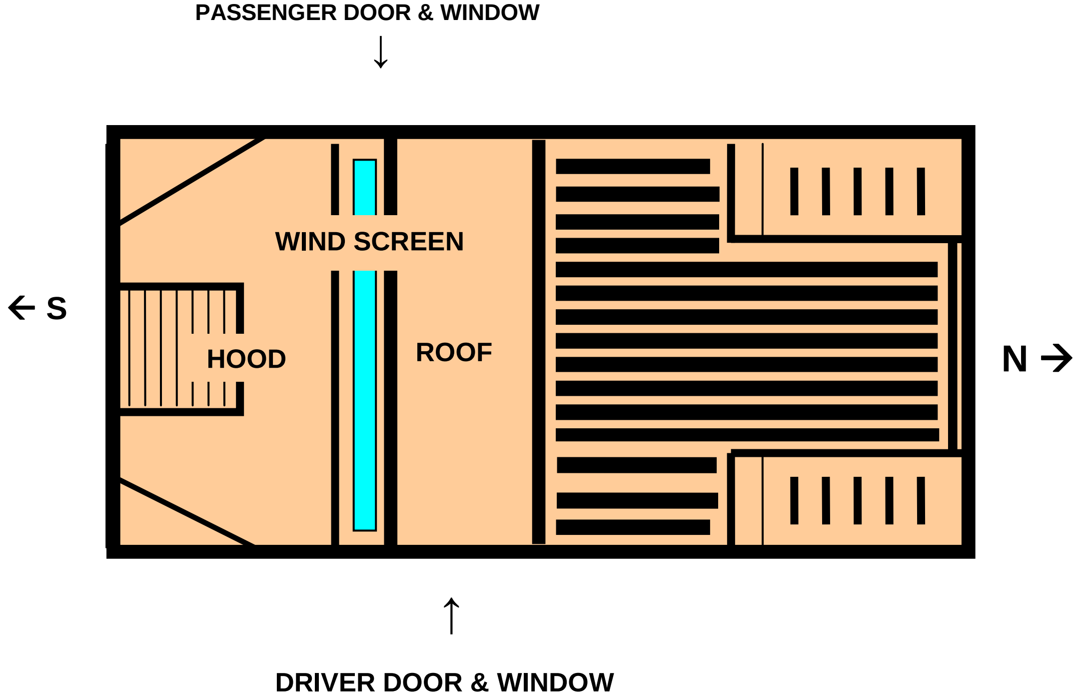
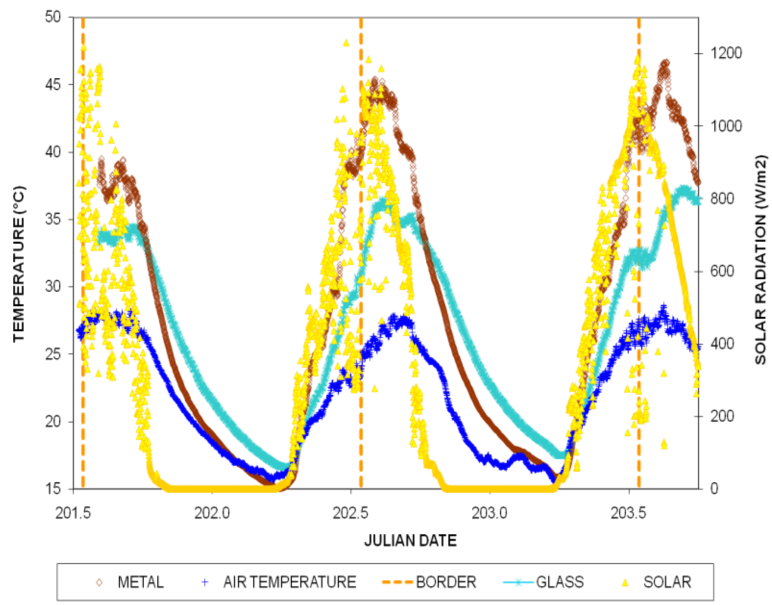


Figure 23. Exterior air and HMMWV surface temperatures plus solar radiation, 20-22 July 2007, are shown. The mean metal temperature is the un-weighted mean of the roof, hood, back panel of cab, driver and passenger door panels. The mean glass temperature is the un-weighted mean of the wind shield, and 2 side windows.



Interior Measurements.

Sensors included a shielded HMP 45 temperature/ humidity sensor, cooper-constantan thermocouples for air and surface temperatures, a black globe thermometer, and spot checks of ventilation with hot-wire anemometer. The placement of temperature sensors is summarized in Tables 5 and 6. The "PVC Man" mount, as described earlier (Figure 11), was used in the passenger seat to measure black globe temperature at head level and air temperatures at head, center of mass, thigh/knee, and calf levels. AC vents were monitored by placing thermocouple sensors in the vents. The driver's side left vent was measured on a channel recorded by the CR10X weather station datalogger. Other interior surfaces measured were the engine housing, windshield, and window glass, dash, and roof. Interior and exterior monitoring was supplemented with FLIR thermal images, as described and shown earlier (Figures 6 and 7).

Table 5. Interior Thermocouple Placement using Surface Sensors and the PVC Mount.

Variable	Location	Comments
Globe Temperature	Head	PVCMAN air
Air Temperature	Head	PVCMAN air
Air Temperature	Center Of Mass	PVCMAN air
Surface Temperature	Seat Back	Surface sensor
Air Temperature	Thigh/Knee	PVCMAN air
Surface Temperature	Seat	Surface sensor
Air Temperature	Calf	PVCMAN air
Surface Temperature	Foot/Floor	Surface sensor

Table 6. Interior Sensor Placement including Shielded Air Temperature and Humidity, Driver and Dash Measurements.

Variable	Sensor	Location
Air Temperature	Shielded HMP 45	Center Cabin
Relative Humidity	Shielded HMP 45	Center Cabin
Surface Temperature	Thermocouple	Windshield
Surface Temperature	Thermocouple	Back Panel
Surface Temperature	Thermocouple	Driver Door Glass
Surface Temperature	Thermocouple	Driver Door Panel
Surface Temperature	Thermocouple	Passenger Glass
Surface Temperature	Thermocouple	Passenger Door
Ac Vent Temperature	Thermocouple	Passenger Air Vent
Surface Temperature	Thermocouple	Roof (Center)
Surface Temperature	Thermocouple	Passenger Roof
Surface Temperature	Thermocouple	Driver Dash
Surface Temperature	Thermocouple	Engine Housing

Figure 24 compares external and interior air temperatures measured with shielded HMP 45 sensors. The maximum interior air temperature was 42.6°C versus 31.9°C for the exterior environment. Maximum interior temperatures are associated with the engine-on, no air-conditioning state, but that observation is confounded by the proximity of the measurement to solar noon and maximum outdoor temperatures. The maximum interior surface temperature was 59.0°C for the engine housing. Air velocities (Table 7) were measured with a hand-held hot-wire anemometer. Values were measured by an individual seated on the driver's side of the cab with the engine and ventilation fan operating. Figure 25 shows the effects of operating the engine and air-conditioning on 21 July 07 (Julian date 202) on the hood external temperature, engine housing between the driver and passenger, and the temperature of the air-conditioned air entering the cab.

Figure 24. HMMWV shielded interior and exterior air temperatures measured, 20-22 July 2007. Note short time lag between solar noon (vertical line), exterior air temperature, and interior air temperature. Dip on 20 July (J=201) was due to open doors. Air conditioning was used on 21 (J=202) and 22 (J=203) July.

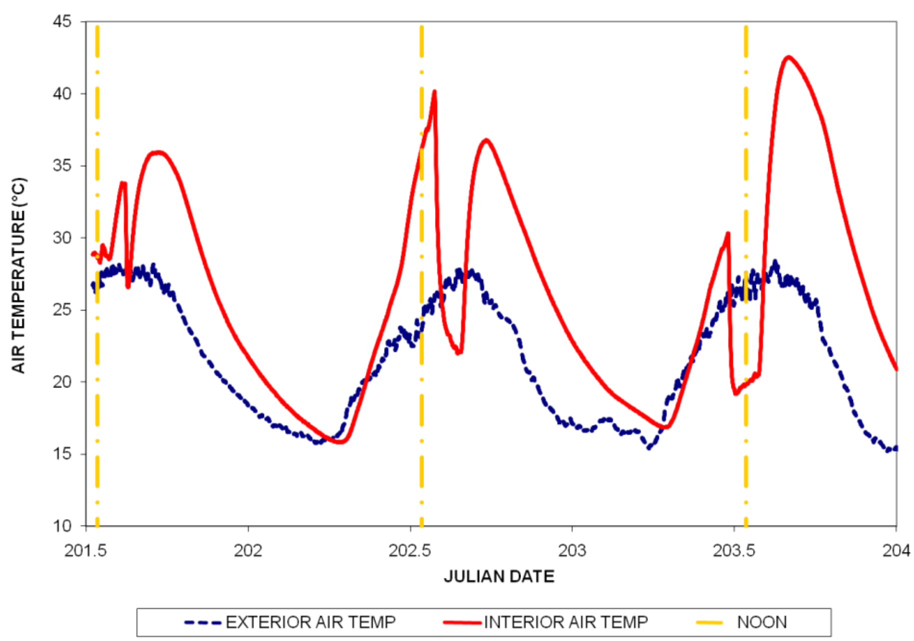


Figure 25. Surface and vent temperature, 21 July 2007, showing effect of engine operation and air conditioning. Engine housing is located between driver and front passenger.

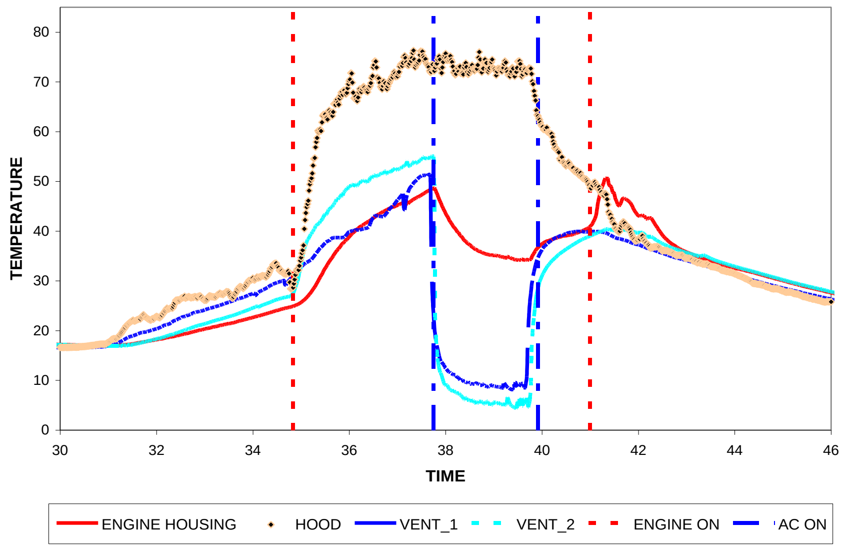


Table 7. Results for Measurements of Air Velocities Measured While Seated Inside the HMMWV with Windows Closed, Engine Operating with Fan

HMMWV Air Velocities

Air Vents	Values (m/s)
Driver Left	6.8
Driver Right	5.1
Passenger Left	3.5
Passenger Right	13.9
Driver's side	
Head	1.8
Left Arm	0.2
Right Arm	0.9
Chest	0.5
Thigh	0.1
Shin	<0.1
Feet	<0.1
Passenger's side	
Head	0.2
Left Arm	0.7
Right Arm	1.3
Chest	0.5
Thigh	0.7
Shin	0.5
Feet	0.2

BRADLEY FIGHTING VEHICLE (BFV)

The interior and exterior thermal environment of the Bradley Fighting Vehicle (BFV) was measured at the Yuma Proving Ground on 28-30 August 2007. As previously described for the other case histories, external conditions (air temperature, relative humidity, wind speed and direction, global solar radiation, ground temperature, and barometric pressure) were measured using a CSI CR10X-based weather station and a QuesTemp34° WBGT monitor (Quest Technologies, Oconomowoc, WI) with a 5 cm globe thermometer. The maximum and minimum observed outdoor air temperatures were 45.9°C and 29.9°C, respectively. Mean-shielded outdoor temperature at 1.5 m was 37.7°C. Figure 26 shows the air temperature, relative humidity, and WBGT index on 29 August 2007.

For data collection purposes, the interior thermal environment, as shown earlier in Figure 3, was divided into three zones: the driver compartment, the command/ weapons turret, and passenger area. The driver is seated in a tight compartment on left front, with the engine to right and behind the driver with a narrow passageway on the left that connects to the rear passenger area (Figure 27). From the passenger area, there is a step up into a centrally located turret area for the BFV Commander and Gunner (Figure 28).

Figure 26. Yuma Proving Ground weather, 29 August 2007. Sunrise, solar noon, and sunset shown by vertical lines.

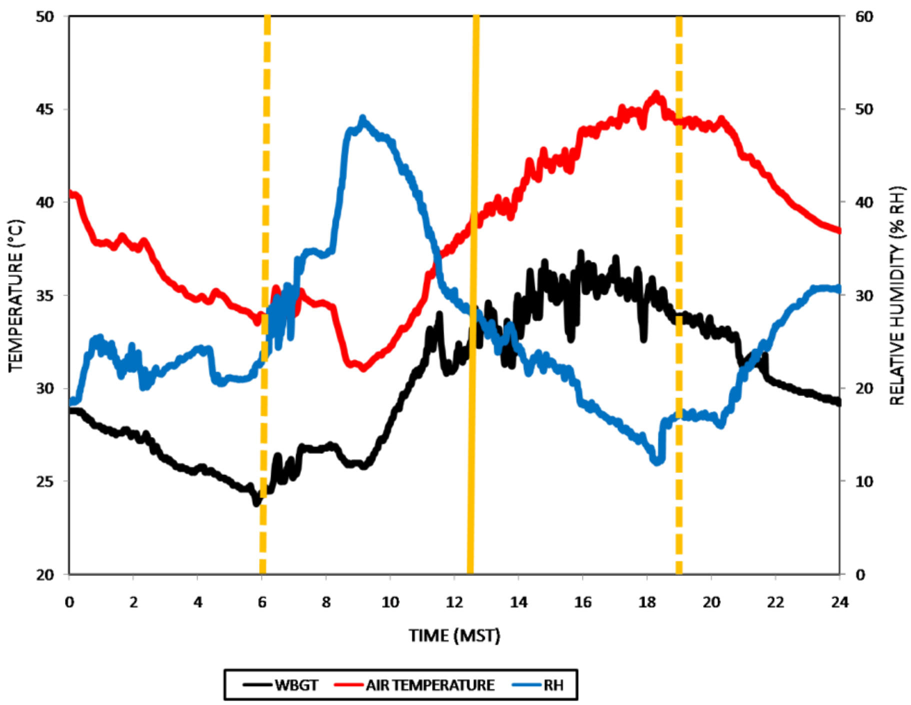


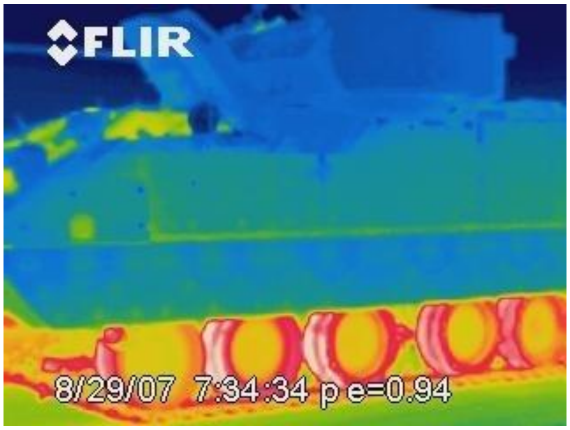
Figure 27. Two views of driver's compartment BFV with sensors in place. HOBO v2 are located on engine access panel to driver's right rear and left front at edge of hatch. Black globe is in passageway behind driver. Curved area behind black globe is the turret wall.

Figure 28. Passenger compartment – BFV with ramp open showing placement of black globe thermometer, shielded temperature/humidity sensor, dataloggers on bench opposite occupants, entrance to turret background center and passageway to driver's compartment, left background. Image with two investigators also reflects relative tight quarters for six fully equipped infantrymen.

Sensors inside the BFV recorded 40 interior air and surface temperatures, 2 black globe temperatures, and relative humidity at 9 sites (Table 8). Exterior surface temperatures were measured at 5 sites, and 2 tilt sensors (model CXTA02 two-axis tilt sensor, Crossbow Technology, San Jose, CA) were secured on the driver and turret hatches. The tilt sensors captured whether the hatch was open or closed and provided

a rough indication of vehicle motion. In addition, air velocities were measured at vents, and infrared images (FLIR) were recorded when the vehicle was parked between runs. Figure 29 shows an outside thermal image of the BFV after trial runs. The intensity of the red color of the vehicle tracks indicates heat generated during runs.

Figure 29.   Exterior Forward Looking Infrared (FLIR) thermal image taken after test run showing heat build-up on track.



The majority of interior surface and air temperatures and the 5 exterior surface temperatures were measured with copper-constantan thermocouple thermometers recorded with CSI CR7 and CR21X dataloggers. Humidity was monitored with an HMP 45 temperature/ humidity sensor with a Gill Shield (CR23X) in the passenger area and 8 HOBO pro v2 temperature/humidity sensors. The HOBO units provided 8 air temperatures. Figure 30 shows a thermocouple surface temperature sensor and a HOBO in the passenger area. In most cases, an alcohol spray was used to clean the surfaces before the thermocouples were taped to the interior and exterior vehicle surfaces.

Figure 30. Placement of HOBO v2 temperature and humidity sensor and copper constantan thermocouple (under tape) on wall of BFV passenger compartment.

Data were collected continuously while the BFV was parked, idling, moving between test courses, and traversing test courses. During testing and movement to and from the test courses, the BFV was driven ~100 km at a top speed of ~55 km/h. The BFV was parked in the open on a sand surface one night, and the next night on a concrete slab underneath a metal roof. Data were collected with the driver hatch closed and open while navigating and traveling between courses. Table 9 summarizes the maximum temperatures measured inside the BFV. Figure 31 plots compartment temperatures for the driver, vehicle commander, gunner, and a passenger seat. The figure also indicates when the driver's hatch was opened or closed.

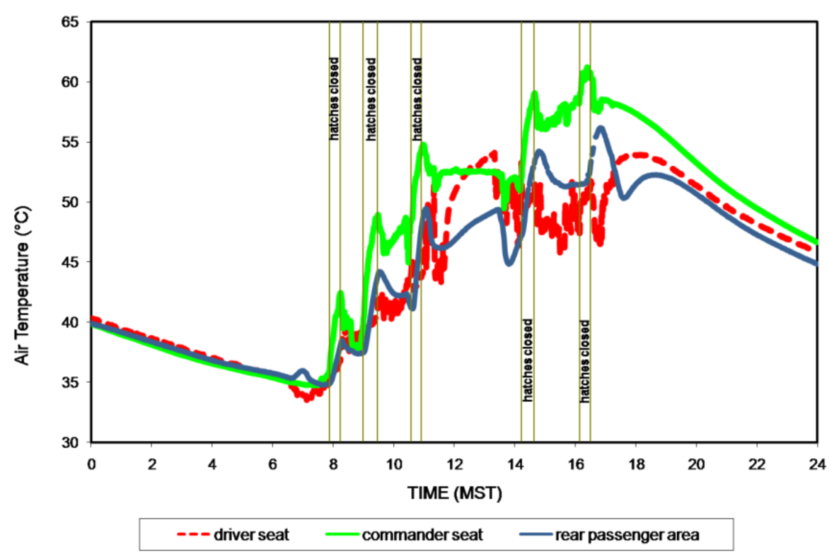
Table 8. Vehicle Measurements.

40 interior air and surface temperature sensors	32 thermocouples, 8 HOBO units
2 black globe temperature sensors	Behind driver and passenger area
5 exterior surface temperature sensors	Tape covered thermocouples
9 relative humidity sensors	(1 HMP 45 and 8 HOBO v2)
2 tilt sensors	Drive and turret hatch covers
wind speed at vents	Hot-wire anemometer
IR thermograms	FLIR images

Table 9. BFV Interior Hot Spots during Testing.

Maximum air temperature in driver compartment (seat level)	56.6°C
Maximum surface temperature in driver compartment (floor)	57.7°C
Maximum air temperature in turret compartment	66.3°C
Maximum surface temperature in turret compartment (right wall)	75.2°C
Maximum air temperature in rear compartment	56.8°C
Maximum surface temperature in rear compartment (floor)	56.5°C

Figure 31. Bradley Fighting Vehicle temperatures, 29 August 2007.



A similar study was conducted in an environmental chamber at Aberdeen Proving Ground by Army Research Laboratory (ARL) personnel (10). The same basic study plan was followed, with data collected at three heights for driver, other crew members, and passengers. The ARL study provides a good comparison to the methods described in this report. A second report provided outdoor and vehicle interior temperature for a stationary M-1 Tank (11) at YPG, but the interior values for dry bulb temperature (T_a), RH, and WBGT are reported only as initial and final values for each measure.

CONCLUSION AND SUMMARY

Detailed and accurate measurement of the thermal properties of enclosed spaces is part of the foundation necessary to improve and validate existing biophysical models and to develop new ones. By measuring the internal environment, the level of biophysical thermal stress within the spaces can be determined, and the level of thermal strain (i.e., the change in thermal state of any occupants and, thus, the likelihood of thermal injury) can be estimated. By simultaneously measuring the external environment, extrapolations of the state of the interior environment may be made in situations where it is not possible to obtain direct internal measures. These measurements may also be used to identify and characterize discrete microenvironments within vehicles and structures in support of efforts to improve occupant comfort.

Improvements in sensors and instrumentation will continue. The specific recommendations regarding sensors and data collection systems will become dated, if not obsolete. Our understanding of the nature of energy exchange will also continue to improve. As the biophysical models evolve over time, there will continue to be a need to collect the basic information regarding the thermal properties of enclosed spaces – temperature, humidity, air velocity, and radiation – in order to validate and improve those models.

Research methods and the metrology necessary to implement them are often of necessity ad hoc. Vehicle interiors and other militarily relevant spaces differ and will continue to change. However, the following general guidelines may be useful in developing a systematic and consistent approach to evaluating the thermal environment of enclosed spaces:

1. Measure the same parameters as outdoors – temperature(s), humidity, air movement, and radiation. These physical properties determine the potential for heat exchange for occupants of an enclosed space by convection (C), conduction (K), radiation (R), and evaporation (E).

2. There are typically a number of microclimates, effects from surrounding surfaces; thus, generally greater numbers of more complex measurements may be necessary than when making outdoor measurements. When planning data collection, investigators should seek input from users, designers, and other individuals with hands-on

knowledge of the enclosed space and the surrounding environment. Recognizing potential microclimates may not be straight forward or obvious.

3. Air velocity is often low, but directional flow patterns are complicated by drafts and ventilation. Proximity to walls may produce drag and induce turbulence.

4. Walls, ceiling, floors, and other surfaces will all absorb, reflect, and emit radiation; thus, it is important to measure surface temperatures. Consider reflection, especially from smooth or shiny surfaces.

5. Outdoor weather will have an effect on most enclosed spaces, but there will be a lag time dependent on the mass (thermal inertia), volume, insulation, and other properties of the interface between the exterior and interior environments.

6. Investigators should attempt to collect sufficient data to adequately characterize the thermal conditions for each occupied microclimate, as well as to fully describe the spatial parameters of each.

The opportunity to collect data on enclosed spaces and the surrounding external environment does not arise every day, and the investment of resources is significant. Accurate detailed records and measurements are needed to ensure that the full value of the data collection effort is available to the investigative team and any future users.

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APPENDIX
MONITORING COLD ENVIRONMENTS

In the cold, monitoring will usually focus on air and surface temperatures. While RH may be high in the cold, the gradients that drive evaporative heat loss are large, and any warming of cold air will result in conditions favorable to rapid evaporation. During winter, solar radiation comes at low angles and, regardless of season, may be strongly reflected off ice or snow. At lower solar angles, direct beams through windows are more common, but the number of daylight hours is significantly reduced, and the intensity of the radiation may be reduced.

The impact of the environment on the thermal state of Warfighters is often described in terms of wind chill (A1, A2, A3). Wind chill temperature (WCT) is based on modeling of the rate of cooling of the exposed face. WCT is not directly related to whole body cooling (hypothermia), nor is it fully applicable to the potential risk to bare skin on other body parts. Originally, wind-chill was described in terms of “cooling power” rather than temperature. Although wind-chill was almost immediately controversial (A3), misconceptions were exacerbated when wind-chill was expressed as a temperature. WCT is not an actual temperature that can be measured with a thermometer. It is a derived value, expressed in units of temperature, defined for a specific set of conditions. Users need to understand that wind chill is based on the rate of cooling. In practical terms, WCT has only limited utility as an indicator of how rapidly a person or object will cool. A person or object can only cool to the point where it is in equilibrium with the surrounding environment. Under most circumstances, that means that an object can only cool to a value ≥ Ta. If the air temperature is above 0°C, water and human tissue do not freeze, although some non-freezing injury may occur. Another effect related to the actual temperature is that some materials, such as metals or rubber, may become brittle at extreme temperatures. It should be stated categorically that describing a cold thermal environment solely by WCT without reference to the actual air temperature is wholly inadequate. WCT has no application in enclosed spaces.

In the cold, within an enclosed space, the impact of the outside wind on occupants is minimal. For an enclosed space with few windows, the main external influence on interior conditions will be the outside air temperature and the insulation provided by the structure. The air temperature inside a small unheated, uninsulated metal shed or tent will respond quickly to outside air temperatures. Snow cover can isolate a building from outside air temperatures and incoming solar radiation, and can potentially slow heating or cooling. Windows may allow the entry of radiation, but can also be a heat sink and are often the source of drafts. Surface condensation and frost formation may be a problem in cold shelters, as warm moist air contacts cold surfaces.

The relative risk of frostbite and hypothermia vary with conditions. Both may occur with prolonged exposure to cold air, but contact with cold surfaces, such as super-cooled metal, may quickly result in frost-nip or frostbite. Contact of large areas of body surface with cold substrates, like the ground or a wall, will also accelerate general body cooling and hypothermia, but frostbite is a more rapid response if bare or poorly insulated skin surfaces are exposed to cold surfaces. Non-freezing cold injury refers to

injuries that occur when tissue temperatures are cooled but remain above the tissue freezing threshold (-0.5°C).

Collecting data in the cold may present unique challenges. The operation of electronic sensors and data acquisition in extreme cold is also a challenge. Sensors may not be rated for extreme cold. Contact with cold surfaces can result in contact "burns," wires and plastic may become brittle, and battery life may be limited. The protection of data loggers in the cold may involve placing the equipment in an insulated container, such as a food cooler, and providing an appropriate heat source. A small, low-wattage, incandescent light bulb may provide enough heat to keep the equipment and batteries within their specified temperature range.

Data collection outside of enclosed spaces may be even more challenging as the combination of low temperature and wind rapidly cools instrumentation. A detailed description of equipment used to monitor outside weather, and a description of data collection during one study is provided in Santee and Hoyt (A4).

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